Magnetic Sensors Project

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LONG-TERM GOAL

Clandestine mine reconnaissance is one of the Navy's highest priorities. During the 1980's, the Superconducting Gradiometer/Magnetometer Sensor (SGMS) was demonstrated in the Magnetic and Acoustic Detection of Mines Advanced Technology Demonstration (MADOM ATD) to provide effective detection/classification capabilities, especially against buried mines, and to reduce significantly acoustic false alarms arising from bottom clutter [1]- [3]. This sensor utilized Superconducting Quantum Interference Devices (SQUIDs) manufactured using the low critical temperature (low T_c) superconductor niobium and required liquid helium for sensor cooling. Advanced magnetic sensor approaches are being developed to transition this technology to the fleet.

OBJECTIVES

The current focus of this project is to develop an advanced High T_c Superconducting Gradiometer (HTSG) prototype cooled by liquid nitrogen and to demonstrate it at sea. This development will make it possible to achieve the long detection ranges and superior classification and localization capabilities previously reserved to low T_c sensors such as the SGMS. In comparison to its low T_c counterpart, the HTSG can provide substantially reduced package sizes and minimal cryogen support requirements.

APPROACH

The technical approach for this project involves the following phased efforts: (1) preliminary sensor concept design, (2) development and laboratory evaluation of key sensor components, (3) sensor development, (4) sensor evaluation in motion studies simulating underwater and airborne tow operation, and (5) sensor at-sea testing. In FY 1998 work focused on final assembly and initial evaluation of the HTSG superconducting electronics assembly and parallel development and testing of individual elements for the field-deployable room-temperature electronics.

WORK COMPLETED

Exploratory Research and Concept Development: A number of high-T_c magnetic sensing circuits have been developed in conjunction with this project. Sensitivity of 0.026 picotesla/Hertz$^{1/2}$ (pT/Hz$^{1/2}$) at 1 Hz was reported for a magnetometer in the class being utilized in the HTSG [4]. A gradiometer circuit with monolithic thin-film loops providing common-mode signal subtraction prior to signal amplification was demonstrated to have a sensitivity of 54 pT/m-Hz$^{1/2}$ at 1 Hz. This represents one of the best results reported for such a device [5]. A 3-axis magnetometer prototype has been developed and is now available as a commercial product from Tristan Technologies. It provides sensitivities in field operation of 0.14 pT/Hz$^{1/2}$ at 1 Hz, a factor of 50 better than typical performance from a commercial fluxgate. This sensor features a long hold-time, compact dewar and miniaturized electronics with a laptop PC replacing commonly-used benchtop electronics to provide highly

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automated, versatile, user-friendly control and data acquisition [5]-[7]. A number of other results of fundamental high T_c research and device development conducted under this project have been reported [8]-[12].

In order to circumvent the current limitations in high-T_c fabrication technology, a HTSG sensor approach is being pursued which features the three-sensor gradiometer (TSG) concept [13]. This TSG concept recently has been pursued successfully using room-temperature fluxgate magnetometers demonstrating sensitivity better than 300 pT/m-$Hz^{1/2}$ at 0.1 Hz in motion [14]. Use of high-Tc SQUID magnetometers in place of fluxgate magnetometers is being pursued to attain 100-fold increases in sensitivity with corresponding increases in detection range greater than a factor of 3.

Designs of nitrogen cooling units have been established and analyzed in order to provide a range of concepts appropriate for different missions [3], [15]. One design with a 17" diameter and 30" length features a long cryogen hold time of 33 days and a temperature stability of 10^{-4} Kelvin/$Hz^{1/2}$ at 0.1 Hz. (This represents a reduction of 2 in volume and an increase of 8 in hold time in comparison to the helium dewar utilized for the low-T_c sensors.) Another design for ultracompact packaging features dimensions reduced down to 12" in diameter and 18" in length without a loss of sensitivity (although there would be losses in hold time). Further decreases in size allowing ultracompact packaging are projected given more aggressive design approaches. One design of a closed-cycle (non-venting) dewar concept has been developed to eliminate entirely the need for cryogen support. In this case, the sensor operates continuously during a mission lasting up to 16 hours and is re-cooled between missions by an auxiliary active cryocooler.

Development of HTSG Superconducting Electronics Assembly: The superconducting electronics assembly for one version of this HTSG concept has been manufactured. This prototype has 6 SQUID-magnetometer channels to synthesize 3 tensor gradient components. Advanced flux-lock loop (FLL) electronics with a modulation frequency of 16 MHz, 100 times faster than conventional schemes, have been developed to improve cryogenic signal amplification and electromagnetic immunity essential for field operation. A benchtop version of the FLL electronics has been demonstrated with both low-T_c and high-T_c sensors. Closed-loop bandwidth of 2.5 MHz under laboratory conditions has been achieved [7], [16], [17]. These electronics, modified with noise-suppression circuits, have been utilized successfully in the stationary testing of the HTSG laboratory prototype described below. Field Control Electronics (FCE) to maintain constant field at the SQUID magnetometers have been developed with a stringent design and validated through stationary testing not to deteriorate the performance of the SQUID magnetometers. The field control is essential to provide the resolution and dynamic range for magnetometer subtraction and minimization of SQUID noise from flux motion.

Evaluation of the HTSG Superconducting Electronics Assembly: In preparation for field testing, a new data acquisition system was installed at the remote CSS Motion Test Facility in FY 1998 to provide high-fidelity data collection and onsite data analysis and plotting to eliminate the need for time-consuming, inefficient post-processing. Data acquisition software has also been developed and validated to synthesize the tensor magnetic-field gradients from magnetometer signals and to perform the spectral analysis including motion compensation required to ascertain sensor performance.

An initial series of stationary tests on the HTSG using liquid nitrogen for cooling were completed at the CSS in FY 1998. Effective sensor grounding, line isolation, and RFI shielding procedures for the HTSG configuration were established. All major components of the sensor are functional and operating reliably and reproducibly. Additional mechanical analysis has been conducted to predict the

effect of structural deformation on HTSG performance in motion and to establish approaches to compensate any such effects.

Development of a Miniaturized Electronics Assembly for Sensor Field Deployment: A compact field-deployable room-temperature electronics assembly is being developed to replace the benchtop FLL electronics and to provide automated sensor control, signal digitization, and data linking for field deployment. Miniaturization of the electronics into a single integrated unit mounted onto the sensor, in a manner that does not limit sensitivity in motion, represents a major undertaking. The design of the electronics architecture and packaging has been established. Prototype elements of preamplifier, analog, and digital electronics have been manufactured and evaluated. Based on the results from the prototype evaluations, complete sets of these electronic units for the field-deployable assembly have been manufactured. A data link to control individual channels and to multiplex their outputs has been designed and assembled and is currently being evaluated with the digital electronics. An initial test of these new electronics integrated with SQUID magnetometers was conducted in FY 1998.

RESULTS

Evaluation of the HTSG Superconducting Electronics Assembly: The sensor's white noise stationary magnetically unshielded in the CSS field environment is at the same level obtained by the manufacturer in a shielded laboratory environment. Sensitivity of 3 pT/m-Hz$^{1/2}$ at 0.1 Hz has been realized stationary. This figure represents a 20-dB increase in sensitivity at low frequency (and a corresponding 80% increase in detection range) over the level attained during contractor preacceptance

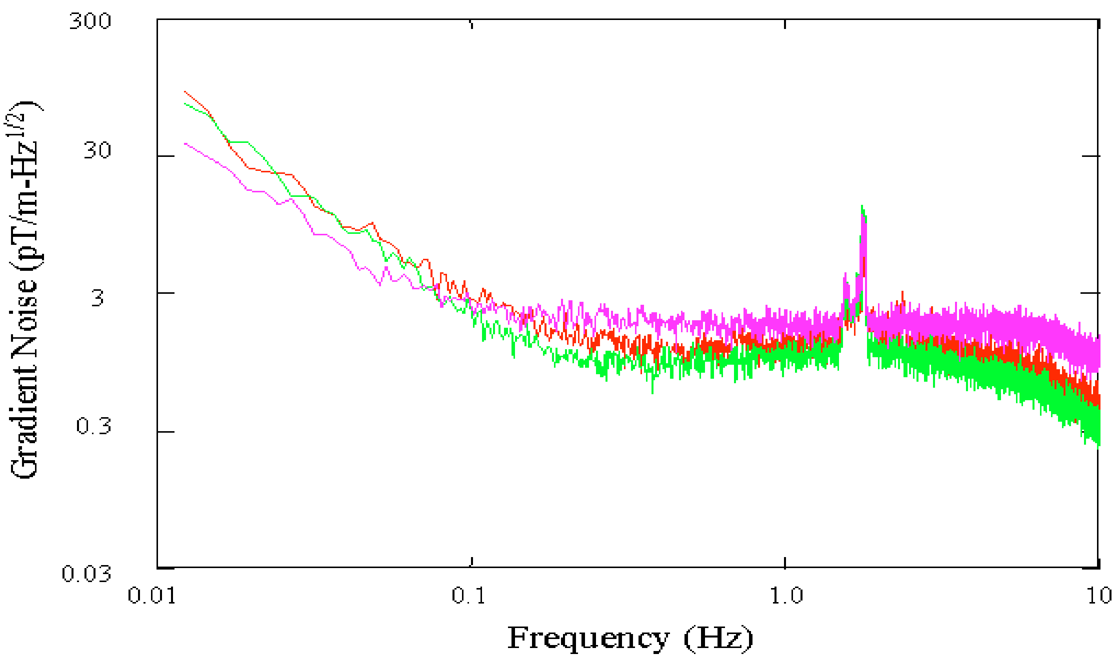

Figure 1. Low frequency stationary gradient noise spectra for 3-channel High T_c Superconducting Gradiometer totally unshielded under field conditions and with Field Control Electronics activated.

testing. It equals the level attained typically by the helium-cooled SGMS in motion. This sensitivity corresponds to a detection range of 50 meters against a 2000-lb bomb.

The 16-MHz FFL electronics with (bias-reversal) low-frequency noise suppression circuits have worked effectively in this unshielded environment. The breakpoint for 1/f noise occurs at 0.5 Hz, which represents one of the best results reported to date for high T_c SQUID magnetometers. No deleterious effects from RFI, in particular very infrequent flux popping, have been observed in this testing. In other words, the enhanced slewing capability of the 16-MHz FLL electronics is effective.

Although the current generation of SQUID magnetometers is susceptible to increased noise when subjected to field change, FCE field nulling has been demonstrated effective to circumvent this problem. In addition, the FCE field nulling is responsible for 10-dB in noise suppression compared to performance obtained without nulling. FCE field nulling reduces the density of magnetic flux trapped in the SQUID magnetometer that, in turn, reduces noise from thermally-activated flux motion.

Packaging approaches essential for robust, reliable field performance have also been implemented. Hermetic sensor packaging has proven effective in extending the life of the SQUID sensors with devices working after 3 years of use. Based on this experience, similar hermetic packaging is being pursued by other SQUID manufacturers. In addition, an approach of thermal cycling SQUIDs, first developed for this project, has proven effective in re-establishing optimal state in situations where performance has deteriorated.

Based on mechanical, magnetic, and thermal analysis, HTSG performance attained stationary is projected not to deteriorate in motion. A conceptual approach to compensate for microscopic structural deformation using accelerators has been established and the hardware implemented for the contingency that such an effect is observed. These predictions will be evaluated experimentally in the upcoming FY 1999 motion testing.

Development of a Miniaturized Electronics Assembly for Sensor Field Deployment: 8 analog and digital units have been interconnected and operated through a printed circuit backplane. Data has been transmitted and received simultaneously from all 8 channels without data loss. Noise from the electronics was limited by intrinsic SQUID noise, which is the desired outcome. This validated the design goal for the analog FLL electronics and for 19-bit digitization from the digital units.

IMPACT/APPLICATIONS

The U.S. Navy has pioneered the 5-channel tensor-gradiometer approach for enhanced magnetic target detection, classification, and localization and the technology area of superconducting magnetic sensors for long-range detection in mobile applications. The Navy has demonstrated the utility of these sensors in the MADOM ATD. The Navy's program has supported development of the first commercial dc SQUIDs, electronics to suppress low frequency noise and to provide ultra-wide bandwidths, and large-scale niobium thin film devices for unshielded operation. Advanced dewars have been developed for mobile magnetic sensing and other applications requiring a high degree of thermal and magnetic stability at cryogenic temperature. This project has supported substantive refinement in high-T_c magnetic sensor technology. The HTSG represents one of the few major accomplishments realized to date from the advent in development of high T_c superconducting electronics a decade ago.

The technology developed in this task can also be applied to the military missions of nonacoustic ASW, the detection of underground facilities and hidden military targets, extremely low frequency communications, and torpedo homing. The approach can be utilized for a wide range of dual-use applications including environmental cleanup, geophysical survey, archeology, and treasure hunting. It can also be applied to police operations for the location of buried or sunken cars, planes and boats and to civil engineering for the location of underground or undersea cables, pipelines, old foundations, buried gas tanks, and well heads. The SQUID technology is more generally being pursued for biomedical research and non-envasive clinical examination and for nondestructive evaluation, especially with the advent of the high T_c scanning SQUID microscope.

TRANSITIONS

One low-T_c sensor technology transitioned to the MADOM 6.3 Advanced Technology Demonstration in FY 1989 and to the Buried Mine Detector (BMD) 6.4 Program in FY 1992. Although the BMD Program is not currently funded, the advanced HTSG prototype from this project is available for transition to support reconnaissance and hunting operations, notably for the Remote Mine Hunting System (RMS). The low-T_c technology from MADOM has been successfully demonstrated in the FY 1995 Feasibility Demonstration of the Mobile Underwater Debris Survey System (MUDSS) and will be utilized in the FY 1999 Technology Demonstration of MUDSS [2], [18]. The nitrogen-cooled HTSG will be utilized in subsequent surveying for UXO cleanup and related applications. As mentioned previously, a 3-axis magnetometer prototype developed under this project is now commercially available from Tristan Technologies.

RELATED PROJECTS

6.1 research by IBM Research sponsored by ONR 312 (Dr. D. van Vechten) and CSS Internal Research to investigate noise mechanisms in high T_c SQUID magnetic sensors both support this 6.2 exploratory development project. The 6.2 project Man-Portable Tensor Fluxgate Gradiometer Evaluation and Signal Processing Development sponsored by ONR 322 (Dr. J. Kravitz) supports this project through development of the TSG approach using fluxgate sensors and the development of new localization algorithms and related signal processing. The Phase II SBIR to Conductus, Inc. sponsored by ONR 322 (Dr. J. Kravitz) has contributed directly to developments described in this report. The project has also been supported by the VSW Integrated Sensors Project at CSS sponsored by ONR 321 (Dr. R. Jacobson) to investigate approaches for platform magnetic-noise reduction in mine hunting vehicles [19], [20]. The MUDSS Project sponsored by the Strategic Environmental R&D Program is demonstrating the utility of the magnetic gradiometers for underwater survey.

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